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# Dynamic Analysis of Delamination Growth

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## Abstract

THE dynamic problem of the growth of a thin homogeneous strip delamination in a thick base plate under axial loading has been studied with a Griffith-type fracture criterion adopted. The variational equation of motion and the dynamic local growth condition at the crack tip are derived. The resulting nonlinear free boundary problem is solved by a numerical technique that combines both the finite element method and the Newton-Raphson iterative method. The local growth condition at the delamination front is examined at each time step of the integration process. It is found that the ratio of the applied compressive strain to the bifurcation strain of the delaminated layer is an important parameter in determining the delamination growth behavior. The results of the present analysis are compared with those of the quasidynamic analysis.

## Contents

The geometry, material properties, boundary conditions, and loading conditions are important factors in determining the initiation, development, and termination of delamination buckling and growth in a compressed laminate. The effects of these parameters have been chosen as the subjects of considerable research work[1-4] recently. Although the effect of geometrical nonlinearity was taken into account, the inertial effect in the dynamic growth of delamination was ignored in most analyses. However, when the speed of delamination growth is fast, the deflection, force, and moment resultants near the delamination front can be significantly affected by the inertial effect.

In this paper, the dynamic growth behavior of a thin, homogenous, strip delamination in a thick orthotropic base plate under axial loading is studied. The delaminated layer buckles when the compressive strain in the base plate exceeds the bifurcation strain of the layer. Delamination growth then occurs when the strain is further increased to satisfy the local growth condition at the crack tip. Under this circumstance, the energy release rate at the delamination front equals the specific fracture energy of the material. Thereafter, the axial strain is maintained constant as the delamination growth continues. A quasidynamic solution based on static postbuckling deformation and a global energy balance condition was given[5] previously for this nonlinear free boundary problem. This approximate solution is accurate for slow delamination growth speed but becomes unreliable for fast delamination growth rate because the local growth condition at the crack tip is not satisfied and the assumed deflection deviates significantly from the actual dynamic deflection. For the present work, the dynamic growth of the delaminated layer is formulated by a variational principle coupled with a Griffith-type fracture criterion. All the energies, including bending, membrane, kinetic, and fracture, are considered in the derivation. Both the deflection and delamination length are functions of time and take as variational terms. The derived variational equation with the local growth condition at the delamination front is then solved by a numerical technique that combines both the finite element method and the Newton-Raphson iterative method. Because of the symmetry, only half of the delaminated layer is considered. A one-dimensional beam-column model is adopted and divided into elements with two nodal points and four degrees of freedom (i.e., the deflection and rotation at each node). The delamination configuration and the finite element model are shown in Fig. 1. At the initiation of delamination growth, the delaminated layer is divided into 20 elements. As the delamination growth continues, if the length of the element at the crack tip exceeds 1.5 times its original length, a new element is added into the model. With this model, the problem reduces to a system of nonlinear equations of motion and a moving boundary condition at the delamination front with the degrees of freedom at nodal points and delamination length as unknowns. A direct integration method is used to solve this system of ordinary differential equations. Whether the delaminated layer grows or not at each time step is determined by the Griffith type of fracture criterion. The trajectory of the moving boundary in the space-time plane is solved iteratively by the Newton-Raphson method to satisfy the local growth condition. This developed scheme is proven to be reliable and effective in solving the dynamic problems of delaminated growth.

The axial compressive strain in the base plate needed to initiate delamination growth is an increasing function of the specific fracture energy. Let $\alpha$ denote the ratio of this axial strain to the bifurcation strain of the delaminated layer at the begin-

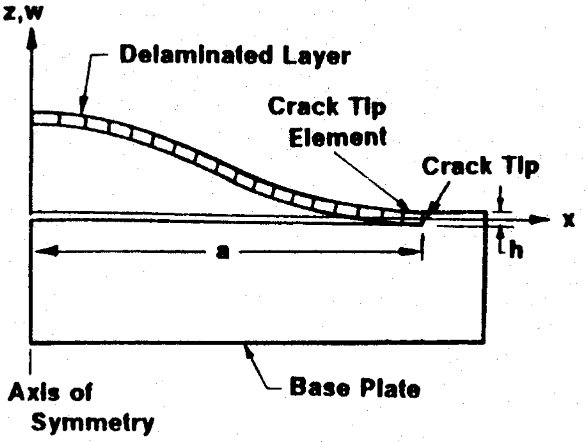


**Fig. 1 Delamination growth model.**

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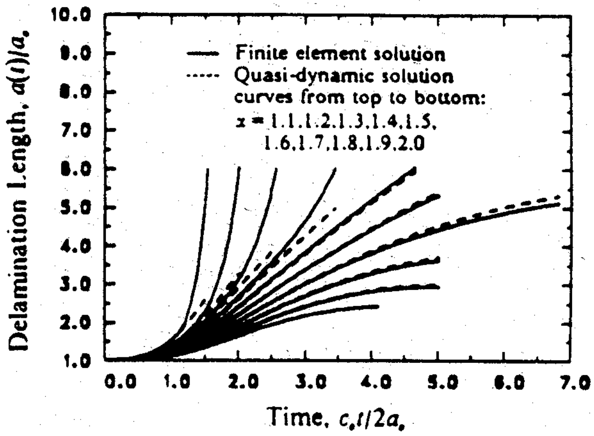


Fig. 2 Delamination growth with time.

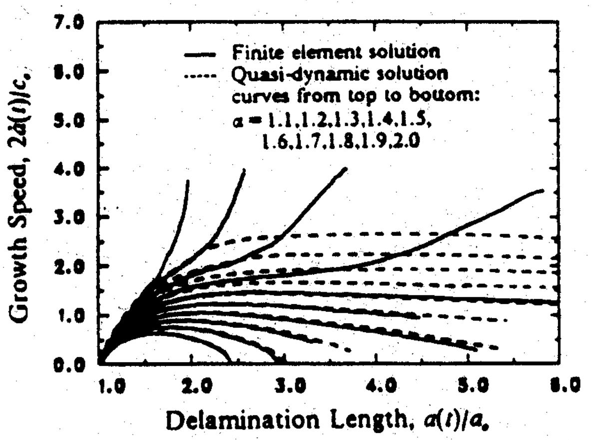


Fig. 3 Delamination growth speed.

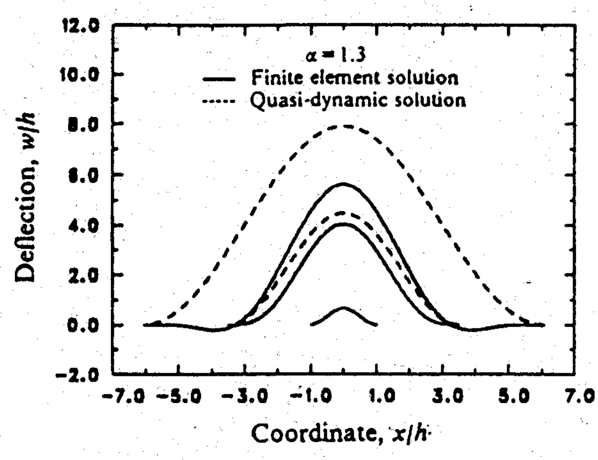


Fig. 4 Delamination profile for $\alpha = 1.3$.

ning of delamination growth, which can be used to characterize the specific fracture energy[5] of the material. From the static analysis of strip delamination for the thin-film model,[1] it is found that the value of $\alpha$ should be between 1 and 3 if delamination growth occurs. The analysis also predicts that for $1.5<\alpha<3$, delamination growth continues until a state of arrest is reached. However, for $1<\alpha<1.5$, delamination grows continually to infinite length. The same conclusions are also obtained with either the quasidynamic analysis[5] or the present analysis. For $1.5<\alpha<3$, the arrested lengths at the end of delamination growth calculated by the present analysis and the quasidynamic analysis are in excellent agreement but give much larger values than those of the static analysis.[1] It shows that for cases with slow delamination rate ($1.5<\alpha<3$), the inertial effect is important and should not be ignored in the calculation of the final arrested delamination length.

Figure 2 shows the change of normalized delamination length $a(t)/a_0$ ($a_0$ is the initial delamination length) with normalized time $c_0t/2a_0$ ($c_0$ is the flexural wave speed) for different values of parameter $\alpha$ from the present analysis and quasidynamic analysis. Figure 3 shows the change of normalized growth rate at the dalamination front $\dot{a}(t)/c_0$ with normalized delamination length $a(t)/a_0$. For $1.5<\alpha<3$, the delamination growth speed increases at first, then decreases to zero and reaches the arrested state. It is found that the maximum growth speed calculated is smaller than the flexural wave speed $c_0$. The fact that the results from the quasidynamic analysis and the present analysis are in good agreement for $1.5<\alpha<3$ suggests that the profile of deflection does not deviate appreciably from that of the static postbuckling deflection.

For $1<\alpha<1.5$, the delamination growth continues all the way and catastrophic delamination growth is predicted by both the present analysis and quasidynamic analysis. Although both analyses indicate qualitatively similar behaviors, they are quantitatively different. In quasidynamic analysis, since the local growth condition at the delamination front is not satisfied, the strain energy release rate can be several times larger than the specific fracture energy. In addition, the actual deflection profile begins to deviate from that of the static postbuckling deflection as the delamination grows. These explain the difference between the two analyses and can be demonstrated by comparing the deflection profiles obtained from both analyses. Figure 4 shows the deflection profiles at the initial and two intermediate states of delamination growth for $\alpha = 1.3$. It is found that the amplitudes of deflection at intermediate states from quasidynamic analysis are in general greater than those from the present analysis and the differences become larger as delamination growth continues. The deflection profiles from these two analyses also deviate significantly at intermediate states. This indicates that besides the fundamental buckling mode, i.e., the static postbuckling mode, which is assumed to be the deflection function in quasidynamic analysis, the higher modes are introduced in the present analysis and become more important with magnified inertial effect.

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